

Mobile Service-Based Cooperative Scheduling for High-Mobility Vehicular Networks

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Abstract—This paper investigates the downlink scheduling for relay-aided high-mobility vehicular networks, where the vehicles with good vehicle-to-infrastructure (V2I) links are employed as cooperative relay nodes to help the ones with poor V2I links forward information via vehicle-to-vehicle (V2V) links. In existing works, instantaneous achievable information rate was widely adopted to perform the link scheduling, but it is not efficient for vehicular networks, especially for high-mobility scenarios. Different from them, in this paper, we introduce the mobile service to describe the mobile link capacity of vehicular networks and then we propose a mobile service based relaying scheduling (MSRS) for high mobility vehicular networks. In order to explore the system information transmission performance limit, we formulate an optimization problem to maximize the mobile service amount of MSRS by jointly scheduling the V2I and V2V links. Since it is a combinational optimization problem which is too complex to solve, we design an efficient algorithm with low-complexity for it, where Sort-then-Select, Hungarian algorithm and Bisection search are employed. Simulation results demonstrate that our proposed MSRS is able to achieve the optimal results with an optimal approximation ratio larger than 96.5%. It is also shown that our proposed MSRS is much more efficient for high-mobility vehicular systems, which can improve the system average throughput with increment of 3.63% compared with existing instantaneous achievable information rate based scheduling method, and with 15% increment compared with traditional non-cooperation scheduling method, respectively.

Index Terms—Vehicular networks, Link scheduling, Mobile service amount.

I. INTRODUCTION

A. Background

Nowadays, Intelligent transportation systems (ITS) become more and more important in people's daily life, because the fast development of urbanization enables people to spend more and more time within moving vehicles [1] [2]. To support various information services for ITS including on board video in vehicles and real-time transport information dissemination, ever-increasing data are required to be delivered over vehicular networks [3] [4].

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In vehicle networks, there are generally two types of communication paradigms, i.e., vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications [5] [6], where V2I communications provide the connection between vehicles and the Internet via roadside base stations (BS), which can support real-time applications, e.g., online music radio, and V2V communications provide the connection between nearby vehicles via dedicated short-range communications (DSRC) technologies, which can support active safety applications, e.g., variable message signs and ramp signalling on motor ways. Since vehicular networks often suffer from performance deterioration caused by the instability of mobile wireless channel and the variation of network topology, the integration of V2I communication and V2V communication in a single vehicular system recently has attracted more attention [5]- [7].

B. Related work

In order to further improve system performance of vehicular networks, a variety of advanced communication technologies were employed. Among them, cooperative relaying is widely considered as one of the most promising technologies, as it is capable of enhancing the system performance by exploiting transmission diversity offered by relay nodes [7] [8].

With cooperative relaying, the signal attenuation caused by the long distance between the vehicle and BS can be released and more vehicular users can be embraced in the service area with more favorable channel conditions, which consequently yields better communication quality and higher system throughput. To well support cooperative relaying transmissions in vehicle networks, several relaying protocols including amplify-and-forward (AF) and decode-and-forward (DF) were employed, see e.g., [9]- [11]. In [9], it investigated the performance of a V2V cooperative AF relaying scheme for inter-vehicle communications, where optimal power allocation was studied to enhance system performance. In [10], the AF cooperative relaying was employed in downlink vehicular networks and pairwise error probability expression and the achievable diversity gains were analyzed. In [11], it analyzed the performance of a relay selection scheme for cooperative vehicular networks with the DF relaying, where only the "best" relay was selected and the outage performance was discussed.

In relay-aided cooperative vehicular systems, different vehicles have different communication performances over V2I and V2V links so that link scheduling becomes very essential [12] [13]. For example, in a multiple vehicular user system, how to determine which vehicles should be scheduled to communicate with the BS over the V2I links and which ones should be

scheduled to communicate with BS over the two-hop V2I-V2V links may greatly affect the system performance. Moreover, how to establish effective cooperative strategy among the vehicles also has significant impacts on system performance. Thus, some works focused on the link scheduling for relay-assisted vehicular networks, see e.g. [14] [15]. In [14], it proposed graph-based scheduling to achieve the maximum sum rate for vehicular networks, where DF protocol was considered. In [15], it proposed a scheduling scheme based on the multi-choice knapsack problem to jointly optimize the link scheduling and radio resource allocation for V2V links.

C. Motivations

However, all existing works scheduled the V2I and V2V links of vehicular networks on the basis of achievable instantaneous information rate of the links. As is known, to capture the dynamic change of network topology and link quality, link scheduling should be performed periodically. That is, for a given period T , all links are scheduled in terms of the link state information at the beginning of T , i.e., at time t , which lasts the whole time interval of T . In relatively low mobility scenarios, the link state and network topology can be regarded to be constant within each T , so that current achievable instantaneous information rate based scheduling is efficient for T although it is calculated in terms of the instantaneous rates of all links at t . But in relatively high mobility scenarios, the link state and network topology may change greatly even for a small time interval Δt ($\Delta t \leq T$). Therefore, the achievable instantaneous information rate of the link obtained at time t may be very different from that at $t + \Delta t$. In this case, if we still use the achievable instantaneous information rate at instant t to perform the link scheduling over its later period of T , it may be improper and even result in a great system performance loss.

Motivated by this, we focus on the link scheduling scheme design for relatively high mobility vehicular networks in this paper. Such a high mobility consideration is significant because high-way transportation has been widely deployed all over the world, where the total length of the high ways in China has exceeded 10×10^3 km with the maximum speed up to 120 km/h and that in USA has exceeded 88730 km with the maximum speed up to 137 km/h in some states.

D. Contributions

We consider a heterogenous vehicular system, where the V2I link and the V2V link adopt different wireless protocols and utilize different communication resources. Specifically, V2I link delivers information via the Third-Generation Long-Term Evolution advanced version (LTE-A) and V2V link delivers information via the DSRC protocol. Since compared with the uplink communication, the downlink communication in which the BS transmits Internet data to the vehicular nodes (VNs), has much larger volumes of data to deliver, we investigate the downlink scheduling for the system.

The contributions of this paper are summarized as follows.

Firstly, we introduce the mobile service amount to characterize the information transmission capacity of high-mobility

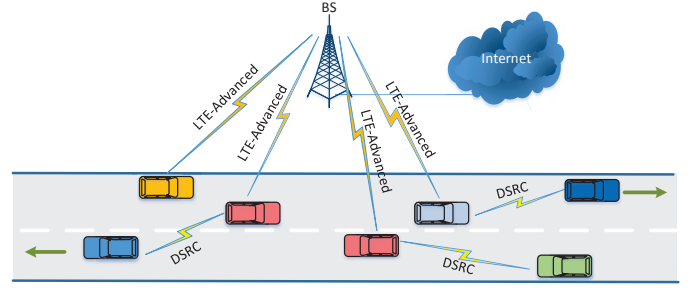


Fig. 1. Heterogenous vehicular network model composed of V2I and V2V links

V2V and V2I links. Based on this, we investigate the optimal relaying scheduling scheme to maximize the system total mobile service amount. Our proposed mobile service based relaying scheduling (MSRS) is very different from existing achievable instantaneous information rate based relaying scheduling (IRRS) which aimed to maximize the sum rate of vehicular systems. Since mobile service is the accumulating information transmission amount over a given time period T , it can adapt to the fast variation of the link state and the fast change of vehicular network topology. Thus, our proposed MSRS is more efficient for high mobility vehicular networks.

Secondly, to explore the system performance limit of our proposed MSRS, we formulate an optimization problem for it. Since the problem is too complex to solve, we design an efficient algorithm with low-complexity. Specifically, the VNs with high V2I mobile service amount are scheduled as helping relaying vehicles (RV) and those with low V2V mobile service amount are scheduled as aided vehicles (AV). For a given number of AV, we construct a square benefit matrix and then adopt Hungarian Algorithm to calculate the optimal pairing between the RVs and the AVs. Then we use the Binary search to update the number of AVs to get the optimal solution.

Thirdly, we provide extensive simulation results to compare and discuss the system performance. It shows that, our proposed low-complexity MSRS algorithm can achieve the approximating maximum mobile service amount with a probability larger than 96.5% for vehicular networks. It is also shown that our proposed MSRS is much more efficient for high-mobility scenarios, which enhances the system performance with 3.63% increment, compared with existing IRRS and 15% increment compared with traditional non-cooperation scheduling method, respectively.

The rest of the paper is organized as follows. In Section II, it describes the system model. Section III formulates an optimization problem for our proposed MSRS. In Section V, we design low-complex algorithm for MSRS and provides extensive simulation results in Section VI. Finally we summarizes the paper with some conclusions in Section IV.

II. SYSTEM MODEL

A. Network Model

Consider a vehicular communication system as shown in Figure 1, where N moving VNs on the road desires to

receive data from a common BS located on the roadside. Similar to normal cellular users in LTE-A networks, VNs can communicate with the BS via direct V2I links between the BS and each VN. Due to large propagation path loss, only the VNs relatively close to the BS are able to acquire good communication service and the ones relatively far away from the BS often experience poor communication service. Heterogenous V2I and V2V links are considered, where VNs communicate with each other via DSRC V2V connections while V2I links employ the LTE-A.

To improve the communication capacity for the distant VNs (i.e., the aforementioned AV in Section I-D), the VNs with high communication capacity to the BS are scheduled as relays (i.e., the aforementioned RV in Section I-D) to help the BS to forward data to them. That is, the RV first receives the data from the BS via a LTE-A V2I link and then forwards the received data to the AV via a DSRC V2V link. With such a relaying strategy, the information transmission capacity between the BS and the distant VN can be enhanced. As a result, the total throughput of the whole vehicular network is improved.

In such a system, for RV, it receives data from the BS through the LTE-A link and forwards data through the DSRC link to its AV. Note that RV is also a user of the BS and it also receives information from the BS for itself. For AV, it receives data over the two-hop V2I-V2V relaying path. Actually, in Figure 1 it can be seen that, besides RV and AV, there is another kind of VNs, which just receives information from the BS for themselves without helping any AV. We refer them as common vehicle (CV).

B. Channel Model

It is known that signal strength is the key factor to wireless communication systems, where a strong received signal may yield a high received signal-to-noise-ratio (SNR), consequently a high transmission rate, and a weak received signal may lead to a low received SNR and a low transmission rate.

In vehicular networks, especially in suburban scenarios and viaduct scenarios, scatterers are very sparse, the effect of large-scale fading (propagation path loss) generally is much more serious than that of small-scale fading. Similar to many existing work, see e.g., [16], we ignore the channel variation caused by small-scale fading and assume that the change of received signal strength only depends on the position shifts of vehicles. In this case, the path loss can be expressed as a function of the distance between the transmitter and the receiver as

$$L(d(t)) = L(d_0) + 10\alpha \log_{10} \left(\frac{d(t)}{d_0} \right) \text{dB}, \quad (1)$$

where $L(d_0)$ is the path-loss attenuation at reference distance d_0 , which is affected by the carrier frequency, the heights of the transmitter and receiver antennas, different climate or geology conditions, etc. α is the path-loss exponent (usually $\alpha \geq 2$) and $d(t)$ is the distance between the transmitter and the receiver at time t . As $L(d(t))$ also can be expressed by $L(d(t)) = 10 \log_{10} \left(\frac{P_s}{P_r} \right)$. For a given transmit power P_s , the

received power is

$$P_r = \frac{P_s}{10^{\frac{L(d(t))}{10}}}. \quad (2)$$

C. Instantaneous Achievable Information Rate of the Links

Assuming that all links in the system are additive white Gaussian noise (AWGN) channel with a reference noise power of σ_0^2 . Therefore, at the moment t , the instantaneous achievable information rate between a transmit and its receiver is

$$C(t) = \log_2 \left(1 + \frac{P_r}{\sigma_0^2} \right) = \log_2 \left(1 + \frac{P_s}{\sigma_0^2 10^{\frac{L(d(t))}{10}}} \right). \quad (3)$$

1) *Direct Communications* : For V2I link, it connects the BS and RV or the BS and CV. In infrastructure-based LTE-A system, the communications over the V2I link is based on the LTE-Advanced specification [17], where the entire system LTE radio resources are divided into resource blocks (RBs) along the time and/or frequency domain. Let K_{LTE} be the number of the total available LTE RBs in the system. All VNs share the K_{LTE} RBs to communicate with the BS as shown by the black lines in Figure 2(a). For each VN, it is assigned with $\lfloor \frac{K_{\text{LTE}}}{N} \rfloor$ RBs. Thus, the achievable information rate that the i th VN can enjoy from the BS is given by

$$C_{i,B}(t) = \left\lfloor \frac{K_{\text{LTE}}}{N} \right\rfloor \log_2 \left(1 + \frac{P_B}{\sigma_I^2 10^{\frac{L_{i,B}(d_{i,B}(t))}{10}}} \right), \quad (4)$$

where $L_{i,B}$, $d_{i,B}(t)$, P_B and σ_I^2 are the path-loss, the distance between the i th VN and the BS at time t , the transmit power of the BS and the AWGN noise power over V2I link of each RB, respectively.

For V2V link, it connects the VNs through DSRC links, following the IEEE 802.11p specification [18]. Let K_{DSRC} and n_{AV} be the number of the total available DSRC RBs and the number of AVs in the system. Thus, all n_{AV} AVs share the K_{DSRC} RBs to communicate with each other as shown by the blue lines in Figure 2(a). For each AV, it is assigned with $\lfloor \frac{K_{\text{DSRC}}}{n_{\text{AV}}} \rfloor$ RBs. Similar to the V2I link, the achievable information rate between the i -th VN and the j -th VN is

$$C_{j,i}(t) = \left\lfloor \frac{K_{\text{DSRC}}}{n_{\text{AV}}} \right\rfloor \log_2 \left(1 + \frac{P_i}{\sigma_V^2 10^{\frac{L_{j,i}(d_{j,i}(t))}{10}}} \right), \quad (5)$$

where $L_{i,j}$, $d_{i,j}(t)$, P_i and σ_V^2 are the path-loss, the distance between the i th VN and the j -th VN at time t , the transmit power of the RV and the AWGN noise power over the DSRC link of each RB, respectively.

2) *Two-hop relaying Communications*: As described above, AV's data is forwarded by RV via out-of-band relaying DSRC V2V links. Considering the limitations of process capability and the available transmit power of the nodes and also in order to avoid high signaling overhead and scheduling complexity, we assume that each RV only can help one AV and each AV is only served by one RV at a time. In this case, once a RV is allocated to a AV, the AV will give its assigned V2I RBs to its helping RV and the RV thus can use these RBs to help the information forwarding to AV. This means that, RV does not need to spend its own V2I resources to help the information forwarding, as it has been assigned with

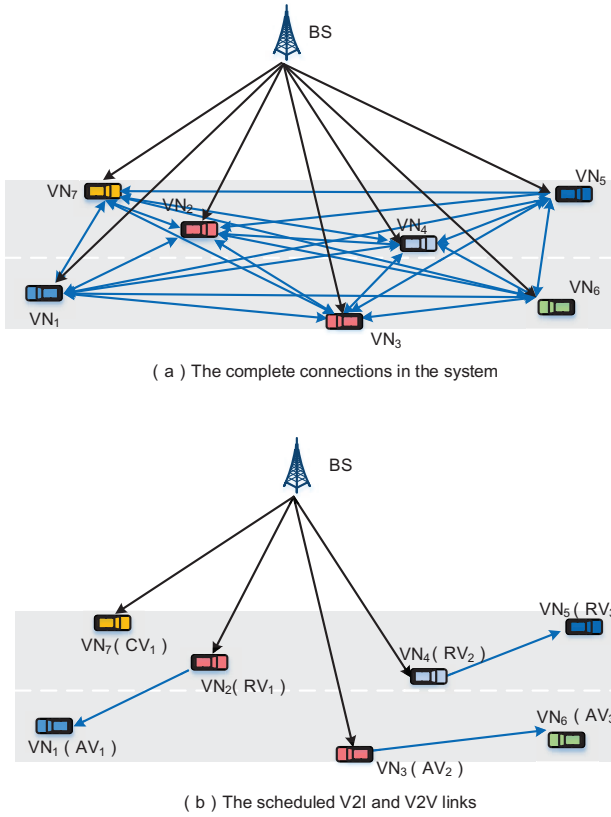


Fig. 2. Illustration of link scheduling in vehicular networks

extra V2I resources for relaying. Therefore, for each RV, its own communication quality with the BS will not be affected when it relays the information for its helped AV. DF relaying protocol is employed applied at the RV. Thus, the end-to-end achievable information rate from the BS to the AV j via helping RV i is bounded by the minimal achievable rate of the two hops, which can be expressed by

$$C_{j,i,B}(t) = \min\{C_{j,i}(t), C_{i,B}(t)\}. \quad (6)$$

III. PROBLEM FORMULATION

Based on the vehicular network system model described in Section II, in this section, we shall discuss how to design efficient scheduling scheme for it. In order to clearly figure out the advantages of our proposed MSRS, we shall first explain the shortcomings of existing IRRS method.

For a downlink vehicular network as shown in Figure 1, its potential connectivity can be illustrated as shown in Figure 2 (a), which looks like a complete graph composed of uni-directional V2I links and bi-directional V2V links. The goal of a scheduling scheme is to achieve the optimal system transmission performance, e.g., the maximum throughput, by jointly scheduling the V2I and V2V links to determine a spanning-tree as shown in Fig 2 (b).

Let $\mathbf{s} = \{\mathbb{N}_{RV}, \mathbb{N}_{AV}, \mathbb{N}_{CV}\}$ be the vehicle division strategy, \mathbb{N}_{RV} , \mathbb{N}_{AV} , \mathbb{N}_{CV} , \mathbb{N}_{VN} denote the set of RVs, AVs, CVs and all VNs respectively. They satisfy that

$$\begin{cases} \mathbb{N}_{CV} \cup \mathbb{N}_{RV} \cup \mathbb{N}_{AV} = \mathbb{N}_{VN}, \\ \mathbb{N}_{CV} \cap \mathbb{N}_{RV} = \emptyset, \\ \mathbb{N}_{RV} \cap \mathbb{N}_{AV} = \emptyset, \\ \mathbb{N}_{CV} \cap \mathbb{N}_{AV} = \emptyset. \end{cases} \quad (7)$$

Let n_{RV} and n_{CV} be the number of vehicles in the set of \mathbb{N}_{RV} and \mathbb{N}_{CV} . We have that $n_{AV} + n_{RV} + n_{CV} = N$. Moreover, because of the relaying constraint, i.e., each relay only serving one AV, thus it can be inferred that

$$n_{RV} = n_{AV} \text{ and } n_{AV} \leq \frac{N}{2}. \quad (8)$$

Let $\boldsymbol{\theta} = \{\theta_{i,j}\}_{n_{RV} \times n_{AV}}$ be the pairing matrix composed by binary element $\theta_{i,j} \in \{0, 1\}$ among the RVs and AVs. Specifically, if RV i is paired with AV j , $\theta_{i,j} = 1$. Otherwise, $\theta_{i,j} = 0$. Since each RV can only be paired with one AV and vice versa, we have that

$$\begin{cases} \sum_{i=1}^{n_{RV}} \theta_{j,i} = 1, \forall j = 1, \dots, n_{AV}, \\ \sum_{j=1}^{n_{AV}} \theta_{j,i} = 1, \forall i = 1, \dots, n_{RV}. \end{cases} \quad (9)$$

If current IRRS is adopted, to maximize the total sum-rate of the system, the system resource is scheduled for each time period T between $[t, t+T]$ by solving the following optimization problem.

$$\begin{aligned} \max_{\mathbf{s}, \boldsymbol{\theta}} \quad & \sum_i^{n_{RV}} C_{i,B}(t) + \sum_j^{n_{AV}} \theta_{j,i} C_{j,i,B}(t) + \sum_\ell^{n_{CV}} C_{\ell,B}(t) \\ \text{s.t.} \quad & (7), (8), (9). \end{aligned} \quad (10)$$

However, IRRS did not fully consider the impact of mobility on vehicular networks. So it cannot exploit the potential achievable transmission capacity, especially for high mobility scenarios. The reason is that, when the vehicle moves very swiftly, the distance between any two communication nodes in the system will change dramatically along with the time within T . Thus, the instantaneous achievable rate calculated at t , i.e., $C(t)$, may have a non-negligible deviation compared with that of $t' \in (t, t+T]$, i.e., $C(t')$. This may degrade system performance. For example, as show in Figure 3, from time t_1 to t_2 , VN_1 firstly moves closer to the BS and then passes by the BS and then moves far away from the BS, and VN_2 moves far way from the BS. At t_1 the distance between the BS and VN_1 is $d_{1,B}(t_1)$ and that between the BS and VN_2 is $d_{2,B}(t_1)$, which change to be $d_{1,B}(t_2)$ and $d_{1,B}(t_2)$. Meanwhile, due to the mobility, the distance between the VNs also changes. The distance between VN_1 and VN_2 increase from $d_{1,2}(t_1)$ to $d_{1,2}(t_2)$. Suppose at time t_1 , VN_1 is determined to communication with BS via the help of VN_2 . At t_2 , this choice may also be not efficient any more because VN_2 is also too far way from VN_1 . Thus, VN_1 should select another vehicle to help it. Moreover, suppose at time t_1 , VN_2 is determined to communication with BS via the direct LET-Advanced link. At t_2 , this may be not efficient any more, due to the long distance between BS and VN_2 .

If one desires to release the impact of mobility and reduce the performance loss by IRRS, the time period T have to

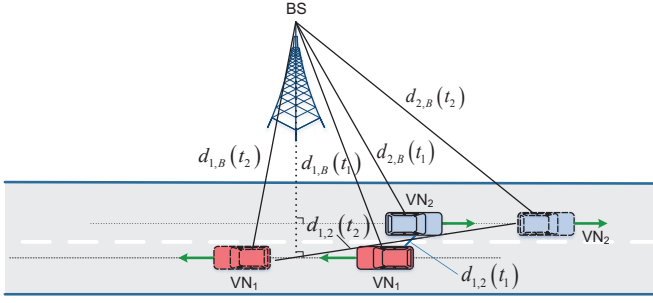


Fig. 3. The impact of vehicle's movement on system performance

be shortened, which however, will result in the increase of signaling overhead and computational overhead. As a result, the system performance may be deteriorated. In order to overcome the shortcomings of IRRS and make the scheduling be capable of adapting to high mobility case, we introduce the mobile service and then present our proposed MSRS.

A. Mobile Service

The concept of mobile service can be traced back to [16], which was proposed to efficiently describe the information transmission capacity of high-speed railway communication system. Here, we introduce it to the heterogenous V2I and V2V coexisting vehicular system.

Due to the channel variation and topology change of vehicular networks, the scheduling should be performed periodically. For the k -th period, the mobile service is defined as

$$S(T_k) = \int_{t_k}^{t_k+T} C(t)dt, \quad (11)$$

where T_k represents the k -th scheduling period, t_k is the beginning time instant of T_k , and T is the time interval of each scheduling period.

It can be seen that the mobile service is an integral of the instantaneous achievable rate over a given scheduling period T , which actually upper bounds the transmission capacity for any given pair of communication nodes, and it represents the maximum amount of data that the physical layer can provide for the network layer.

Substituting (3) into (11), we get

$$S(T_k) = \int_{t_k}^{t_k+T} \log_2 \left(1 + \frac{P_s}{\sigma_0^2 10^{\frac{L(d(t))}{10}}} \right) dt. \quad (12)$$

Parameters in (12) are knowable at time t_k except relative distance $d(t)$. Fortunately, since the movement of the vehicle is limited by the lane and the moving speed of the vehicle can be regarded as constant within a short T . Once the initial position of the vehicle is known at t_k , which can be realized by using the Global Positioning System (GPS), the instantaneous position of the vehicle for any $t \in (t_k, t_k + T)$ can be calculated. The coordinate of the BS is (x_B, y_B) and the position of the i -th vehicle is (x_{i,t_k}, y_{i,t_k}) . v_i is the moving speed of the vehicle and ϕ_i is the angle between v_i and the x -axis of the reference coordinate system. At $t \in (t_k, t_k + T)$, the new position of the vehicle can be

predicted by $(x_{i,t}, y_{i,t}) = (x_{i,t_k} + v_i t \cos \phi_i, y_{i,t_k} + v_i t \sin \phi_i)$. Therefore, at t , the distance between the i -th VN and the BS is

$$d_{i,B}(t) = \sqrt{(y_{i,t_k} + v_i t \sin \phi_i - y_B)^2 + (x_{i,t_k} + v_i t \cos \phi_i - x_B)^2}. \quad (13)$$

and the distance between the i -th VN and the j -th VN is

$$d_{j,i}(t) = \sqrt{(y_{i,t} - y_{j,t})^2 + (x_{i,t} - x_{j,t})^2}.$$

As a result, the V2I mobile service of the i -th VN in T_k can be given by

$$S_{i,B}(T_k) = \int_{t_k}^{t_k+T} \left[\frac{K_{\text{LTE}}}{N} \right] \log_2 \left(1 + \frac{P_B}{\sigma_f^2 10^{\frac{L_{i,B}(d_{i,B}(t))}{10}}} \right) dt \quad (14)$$

and the V2V mobile service of between the i -th VN and the j -th VN in T_k can be given by

$$S_{j,i}(T_k) = \int_{t_k}^{t_k+T} \left[\frac{K_{\text{DSRC}}}{n_{\text{AV}}} \right] \log_2 \left(1 + \frac{P_i}{\sigma_V^2 10^{\frac{L_{j,i}(d_{j,i}(t))}{10}}} \right) dt. \quad (15)$$

Similar to (6), the mobile service of the two-hop communication from BS to the j -th VN via i -th VN also is bounded by the minimal mobile service amount of the two hops. Thus, it can be given by

$$S_{j,i,B}(T_k) = \min\{S_{j,i}(T_k), S_{i,B}(T_k)\}. \quad (16)$$

B. Maximization Optimization Problem for MSRS

The goal of our scheduling scheme is to maximize the total mobile service amount by jointly optimizing \mathbf{s} and $\boldsymbol{\theta}$. Hence our optimization problem can be given by

$$\begin{aligned} \max_{\mathbf{s}, \boldsymbol{\theta}} \quad & \sum_i^{n_{\text{RV}}} S_{i,B}(T_k) + \sum_j^{n_{\text{AV}}} \theta_{j,i} S_{j,i,B}(T_k) + \sum_{\ell}^{n_{\text{CV}}} S_{\ell,B}(T_k) \\ \text{s.t.} \quad & (7), (8), (9). \end{aligned} \quad (17)$$

It can be seen that Problem (17) actually maximize the total information transmission amount over a time period T . For a fixed T , Problem (17) equals to maximize the average system throughput in terms of (bit/s).

Note that, to solve Problem (17) is not trivial, since it is a combinational optimization problem with very high computational complexity if it is solved in an intuitively way as follows.

- 1). Select n_{AV} VNs from the N VNs as AVs to receive data via two-hop communications. (The amount of possible selections is $C_N^{n_{\text{AV}}}$, where C_y^x denotes the x -combinations over y .)
- 2). Select n_{RV} VNs from the rest $N - n_{\text{AV}}$ VNs as RVs to help the n_{AV} AVs. (The number of possible choices is $C_{N-n_{\text{AV}}}^{n_{\text{RV}}}$.)
- 3). Pair the selected n_{AV} AVs with the selected n_{RV} RVs in Step 1 and 2 with a one-to-one manner. (The number of possible pairings is $P_{n_{\text{RV}}}^{n_{\text{AV}}}$, where A_y^x is the x -permutations of y operation.)

- 4). Perform Step 1 to 3 above for $n_{AV} = 1, \dots, \lfloor \frac{N}{2} \rfloor$, where $\lfloor \frac{N}{2} \rfloor$ is the integer floor value of $\frac{N}{2}$. (It can be inferred that, $0 \leq n_{AV} \leq N/2$, as the $n_{AV} = n_{RV}$ and $n_{AV} + n_{RV} + n_{CV} = N$.) Then, select the one with maximum total system service amount as the optimal scheduling.

It can be observed that for each n_{AV} , the computational complexity from Step 1 to 3 is $C_N^{n_{AV}} C_{N-n_{AV}}^{n_{RV}} P_{n_{RV}}^{n_{AV}}$. Thus, total computational complexity of the method above is the summation over all $n_{AV} = 0, \dots, \lfloor \frac{N}{2} \rfloor$, i.e.,

$$\sum_{n_{AV}=0}^{\lfloor N/2 \rfloor} C_N^{n_{AV}} C_{N-n_{AV}}^{n_{RV}} P_{n_{RV}}^{n_{AV}} = \sum_{n_{AV}=0}^{\lfloor N/2 \rfloor} \frac{N!}{n_{AV}!(N-2n_{AV})!},$$

which is extremely complex. Especially, for a relatively large N scenario, this method is unacceptable. Thus, we shall find other way to solve this problem with low complexity.

IV. LOW-COMPLEX ALGORITHM DESIGN FOR MSRS

A. Problem Analysis and Transform

By observation, we can obtain some disciplines for the optimal result associated with Problem (17).

Lemma 1. The optimal solution $\{s^*, \theta^*\}$ of Problem (17) satisfies that, for a AV $j \in \mathbb{N}_{AV}^*$ and a RV $i \in \mathbb{N}_{RV}^*$, if $\theta_{i,j} = 1$, the mobile service amount of the AV over the V2I link must be less than that of the RV over the V2I link, i.e., $S_{j,B}(T_k) \leq S_{i,B}(T_k)$.

Proof: Suppose $S_{j,B}(T_k) > S_{i,B}(T_k)$. Denote $\{s^\#, \theta^\#\}$ be another scheduling which is obtained by picking x out from \mathbb{N}_{AV}^* and then putting x into \mathbb{N}_{CV}^* . It can be easily inferred that the total mobile service amount associated with $\{s^*, \theta^*\}$ is less than that associated with $\{s^\#, \theta^\#\}$. This contradicts that $\{s^*, \theta^*\}$ is the optimal solution. Therefore, Lemma 1 is proved. ■

Lemma 1 indicates that, the VN with smaller V2I link mobile service amount should be selected as AV compared with the one with larger V2I link mobile service amount. Moreover, the CV can be considered as a special RV, which has zero assisted AV. Thus, we can extend θ to be $\theta = \{\theta_{i,j}\}_{(N-n_{AV}) \times n_{AV}}$ and the constraint (9) is refined as

$$\begin{cases} \sum_{i=1}^{1-n_{AV}} \theta_{j,i} = 1, & \forall j = 1, \dots, n_{AV}, \\ \sum_{j=1}^{n_{AV}} \theta_{j,i} \leq 1, & \forall i = 1, \dots, N - n_{AV}. \end{cases} \quad (18)$$

and s is refined to be $s = \{\mathbb{N}_{AV}, \mathbb{N}_{VN} - \mathbb{N}_{AV}\}$. By doing so, the variables \mathbb{N}_{CV} and \mathbb{N}_{RV} are merged into (18) and Problem (17) can be equivalently rewritten by a simpler expression as

$$\begin{aligned} \max_{s, \theta} \quad & \sum_i^{N-n_{AV}} S_{i,B}(T_k) + \sum_j^{n_{AV}} S_{j,i,B}(T_k) \\ \text{s.t.} \quad & (18). \end{aligned} \quad (19)$$

B. Our Proposed Algorithm

Based on these observations, we design an efficient scheduling algorithm with low-complexity, which is composed of the following four steps.

1) **Step 1.** Calculate the V2I Mobile Service Amount: The V2I mobile service amount $S_{n,B}$ for all $n = 1, \dots, N$ can be directly calculated in terms of (14).

2) **Step 2.** Sort all VNs in terms of V2I Mobile Service Amount: The VNs can be sorted in a descending by some typical low-complex sorting methods such as the bubble sorting and the selection sorting. For convenience we denote the set of the sorted VNs as \mathbb{N}'_{VN} .

3) **Step 3.** Find the optimal θ^* for a given n_{AV} : For a given n_{AV} , we select the last n_{AV} VNs in \mathbb{N}'_{VN} as AVs and put them in \mathbb{N}_{AV} , and denote the set composed of the rest $N - n_{AV}$ VNs as \mathbb{N}_{temp} . This means $s = \{\mathbb{N}_{AV}, \mathbb{N}_{VN} - \mathbb{N}_{AV}\}$. In this case, Problem (19) is reduced to be

$$\begin{aligned} \max_{\theta} \quad & \sum_i^{N-n_{AV}} S_{i,B}(T_k) + \sum_j^{n_{AV}} \theta_{j,i} S_{j,i,B}(T_k) \\ \text{s.t.} \quad & (18). \end{aligned} \quad (20)$$

Let $n'_{RV} = N - n_{AV}$. Define a matrix \mathbf{W} , $\mathbf{W}^T = \{S_{j,i,B}\}_{n_{AV} \times n'_{RV}}$, i.e.,

$$\mathbf{W} = \begin{pmatrix} S_{1,1,B} & S_{1,2,B} & \cdots & S_{1,n_{AV},B} \\ S_{2,1,B} & S_{2,2,B} & \cdots & S_{2,n_{AV},B} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n'_{RV},1,B} & S_{n'_{RV},2,B} & \cdots & S_{n'_{RV},n_{AV},B} \end{pmatrix} \quad (21)$$

which can be constructed in terms of (16).

The matrix \mathbf{W} can be regarded as a benefit matrix, whose column indices can be regarded as different operators and row indices can be regarded as different machines, i.e., a total of $N - n_{AV}$ different machines to be operated by n_{AV} different operators. Thus, the value of each entry can be considered as the benefit from operating a specific machine by a specific operator. Then the problem in (20) is equivalent to maximizing the sum benefit via choosing an exactly one element in each row and each column of \mathbf{W} , where each operator is only permitted to operate only one machine. This is a assignment problem.

Case I: $n_{AV} = n'_{RV}$. When $n_{AV} = n'_{RV} = \frac{N}{2}$, \mathbf{W} is square matrix. The assignment problem can be solved by the Hungarian algorithm [19], whose complexity is $\mathcal{O}(N^3)$. For emphasis, the algorithm is described as Algorithm 1.

Algorithm 1 Calculating the optimal pairing over an input square \mathbf{W} .

- Modify all elements in \mathbf{W} in terms of $\max_{1 \leq i, j \leq n'_{RV}} \{S_{j,i,B}\} - S_{j,i,B}$ for all $1 \leq i, j \leq n'_{RV}$;
 - Subtract the elements in each row from the maximum number in the row, and subtract the minimum number in each column from the whole column of \mathbf{W} ;
 - Cover all zero-elements in \mathbf{W} as few lines as possible;
 - If the number of lines equal to the size of \mathbf{W} , the optimal solution is found. Otherwise, find the minimum number that is uncovered. Subtract this minimum number from all uncovered elements and add it into values at the intersections of lines, then go to Step b).
-

Case II: $n_{AV} \neq n'_{RV}$. When $n_{AV} \neq n'_{RV}$, according to (8), it can be inferred that $n_{AV} < n'_{RV}$. In this case, the Algorithm 1

can not be directly adopted because \mathbf{W} is a non-square matrix. Thus, we firstly extend \mathbf{W} to a square matrix $\tilde{\mathbf{W}}$ by adding $n'_{RV} - n_{AV}$ columns with zero-elements as (22).

$$\tilde{\mathbf{W}} = [\mathbf{W}_{n'_{RV} \times n_{AV}} \mathbf{0}_{n'_{RV} \times (n'_{RV} - n_{AV})}] = \begin{pmatrix} S_{1,1,B} & S_{1,2,B} & \cdots & S_{1,n_{AV},B} & 0 & \cdots & 0 \\ S_{2,1,B} & S_{2,2,B} & \cdots & S_{2,n_{AV},B} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ S_{n'_{RV},1,B} & S_{n'_{RV},2,B} & \cdots & S_{n'_{RV},n_{AV},B} & 0 & \cdots & 0 \end{pmatrix} \quad (22)$$

Then, Algorithm 1 can be adopted to calculate the optimal pairing over the extended square matrix $\tilde{\mathbf{W}}$.

The matrix extension process can be explained by the following example. Given a non-square 5×4 matrix \mathbf{W} as

$$\mathbf{W} = \begin{matrix} & \text{AV}_1 & \text{AV}_2 & \text{AV}_3 & \text{AV}_4 \\ \text{RV}_1 & 2 & 3 & 0 & 1 \\ \text{RV}_2 & 3 & 2 & 3 & 6 \\ \text{RV}_3 & 4 & 0 & 3 & 0 \\ \text{RV}_4 & 5 & 2 & 4 & 6 \\ \text{RV}_5 & 1 & 0 & 0 & 2 \end{matrix}, \quad (23)$$

whose row index and column index represents the RV and AV, respectively. Since there are 5 RVs and 4 AVs, one zero-column is added. Thus, the extended square matrix $\tilde{\mathbf{W}}$ is

$$\tilde{\mathbf{W}} = \begin{matrix} & \text{AV}_1 & \text{AV}_2 & \text{AV}_3 & \text{AV}_4 & \text{AV}_5 \\ \text{RV}_1 & 2 & 3 & 0 & 1 & 0 \\ \text{RV}_2 & 3 & 2 & 3 & 6 & 0 \\ \text{RV}_3 & 4 & 0 & 3 & 0 & 0 \\ \text{RV}_4 & 5 & 2 & 4 & 6 & 0 \\ \text{RV}_5 & 1 & 0 & 0 & 2 & 0 \end{matrix}. \quad (24)$$

Then $\tilde{\mathbf{W}}$ is a 5×5 square matrix. Algorithm 1 can be adopted. After performing Algorithm 1 on $\tilde{\mathbf{W}}$, the result is shown as

$$\begin{matrix} & \text{AV}_1 & \text{AV}_2 & \text{AV}_3 & \text{AV}_4 & \text{AV}_5 \\ \text{RV}_1 & 2 & \underline{\underline{3}} & 0 & 1 & 0 \\ \text{RV}_2 & 3 & 2 & 3 & \underline{\underline{6}} & 0 \\ \text{RV}_3 & 4 & 0 & \underline{\underline{3}} & 0 & 0 \\ \text{RV}_4 & \underline{\underline{5}} & 2 & 4 & 6 & 0 \\ \text{RV}_5 & 1 & 0 & 0 & 2 & \underline{\underline{0}} \end{matrix}. \quad (25)$$

where the underlined bold elements are selected as the optimal pairing result. The corresponding optimal θ^* is

$$\theta^* = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad (26)$$

which can be obtained by the following rule as

$$\theta_{j,i}^* = \begin{cases} 1, & \text{if } S_{j,i,B} \text{ is selected and if column } i \text{ is not newly added column,} \\ 0, & \text{otherwise.} \end{cases} \quad (27)$$

According to θ^* , the RVs and CVs can be determined. That is, for the row whose elements are all zero, it is a CV. Otherwise, it is a RV.

4) **Step 4.** Find the optimal n_{AV}^* : According to the Step 3 above, for a given n_{AV} , the optimal θ^* can be obtained in terms of (27) and the corresponding total mobile service amount is

$$S_{\text{tot}}(n_{AV}) = \sum_i^{N-n_{AV}} S_{i,B}(T_k) + \sum_j^{n_{AV}} \theta_{j,i}^* S_{j,i,B}(T_k), \quad (28)$$

which means for different values of n_{AV} , different values of $S_{\text{tot}}(n_{AV})$ can be achieved. Thus, to seek the maximum total mobile service of the network, an appropriate n_{AV} is required to be found.

Remark: There exists an optimal n_{AV} for the proposed algorithm.

Analysis: For a relatively small n_{AV} , only a few vehicles with small mobile service amount are assisted by RVs, which may cause inefficient utilization of the out-of-band DSRC radio resources for V2V links. An extreme case is that when $n_{AV} = 0$, no V2V resource is used. For a relatively large n_{AV} , too many AVs require help from RVs, according to (5) and (15), only a few DSRC bandwidth can be assigned to each AV and the service amount will be limited by the achievable mobile service amount of V2V links, which may result in the decline of the total service amount of the system. Therefore, there is a tradeoff between n_{AV} and $S_{\text{tot}}(n_{AV})$, which means that there exists an optimal n_{AV} for our proposed algorithm.

Based on the above analysis, the optimal n_{AV}^* can be determined by using some fast search methods such as binary section search or golden search. For example, one can initialize $n_{AV} = \lfloor \frac{N}{2} \rfloor$ and $n_{AV} = 0$ for the first and the second round of the extenuation of Step 3. Then, n_{AV} is updated by using the binary section search or golden search. Once the search method stops, n_{AV}^* is determined.

C. Complexity Analysis of our Proposed Scheme

The computational complexity of Step 1 of our algorithm is $\mathcal{O}(N^2)$. The worst computational complexity of the sort method in Step 2 of our algorithm is $\mathcal{O}(N^2)$. The computational complexity of the Hungarian algorithm in Step 3 of our algorithm is $\mathcal{O}(N^3)$ and that of the Binary section search or golden search is $\mathcal{O}(\log_2 N)$. Thus, it can be inferred that our proposed scheme is with a polynomial computational complexity of $\mathcal{O}(N^3 \log_2 N)$.

V. SIMULATION AND NUMERICAL RESULTS

In this section, we present some simulation and numerical results to discuss the system performance of our proposed MSRS with respect to VN's number and VN's moving speed. For comparison, we also simulate the optimal scheme, IRRS and traditional non-cooperation scheme as benchmark schemes. Specifically, for *optimal scheme*, it finds the maximum mobile service amount via exhaustive computer search. For *IRRS*, it draws up the scheduling according to VN's instantaneous achievable rate at the time t_k and its mobile service amount is accumulated over the time interval $[t_k, t_k + T]$ according to its assigned scheduling result. For *the traditional non-cooperation scheme*, it schedules all N VNs to directly communicate with BS without using of V2V links.

A. Simulation Scenario and Parameter Configurations

We simulate the scenario as shown in Figure 1, where the vehicles straightly move on the high way towards two opposing directions. A BS is placed on the roadside with the distance of 15m away from the road, whose position is also considered as the reference point. Each vehicle is represented by a vector (x, y, v) , where x and y are the coordinates of x -axis and y -axis, respectively, and v is the moving speed of the vehicle. (x, y, v) is randomly generated with the limitation of the road area and the vehicle's speed setting. The coverage radius of the base station is set as 0.5km and the vehicle's moving speed is limited within 35m/s. These configurations will not change in the sequel unless otherwise specified.

In the simulations, the V2I communication is performed over LTE-A links, which transmits data via a bandwidth of 40 MHz at a frequency of 2 GHz with transmit power of 52 dBm [17]. The V2V communication is performed over DSRC links, which transmits data via a bandwidth of 5 MHz at a frequency of 5.9 GHz with transmit power of 20 dBm [18]. The path-loss models of V2I and V2V links used in the simulations are given by [17] and [20] as

$$L_{\text{LTE}}(d(t)) = 128.1 + 37.6 \log_{10} \left(\frac{d(t)}{1000} \right),$$

$$L_{\text{DSRC}}(d(t)) = 43.9 + 27.5 \log_{10} d(t),$$

respectively.

B. Performance Comparison with the Optimal Results

Figure 4 and Figure 5 compares the mobile service amount of our proposed MSRS with the optimal results obtained by computer search for $N = 20$ and $N = 40$, respectively. In both Figure 4 and Figure 5, the results of 200 simulations are plotted. It can be seen that the mobile service amounts obtained by our proposed MSRS matches the optimal ones very well for both $N = 20$ and $N = 40$.

To clearly show the performance difference of the two schemes, we sort the 200 simulations in ascending order in terms of the optimal results. The sorted results of Figure 4 and Figure 5 are presented in Figure 6. From Figure 6, it can be seen that the performance difference between MSRS and the exhaustive search is very small, which means that our proposed low-complex MSRS can work well like optimal scheduling.

In order to further quantify the performance loss of MSRS compared with the optimal result. We define the performance loss ratio as

$$\text{Performance loss ratio (\%)} = \frac{S_{\text{opt}} - S_{\text{MSRS}}}{S_{\text{opt}}}, \quad (29)$$

where S_{opt} and S_{MSRS} are the mobile service amount obtained by the exhaustive search and MSRS. In terms of (29) we calculate the performance loss ratio by using 200 simulations in both Figure 4 and Figure 5 and present the results in Figure 7. From Figure 7, it can be seen that the maximum performance loss ratio of MSRS to the optimal scheme is less than 3.5%, which means that MSRS can approximate the optimal results with at least 96.5%.

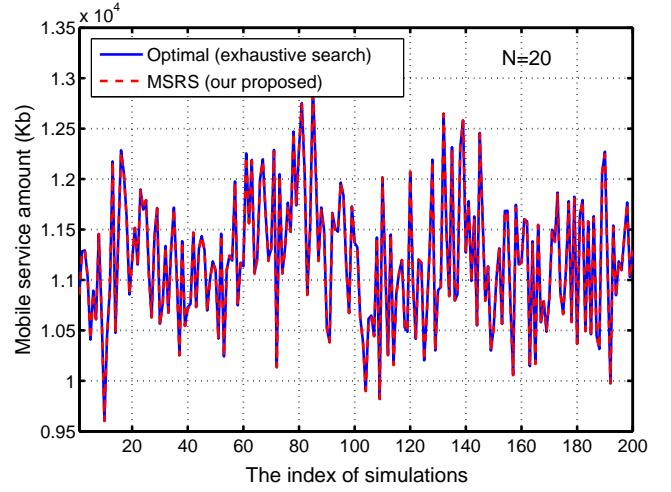


Fig. 4. Total mobile service amount comparison of MSRS and the exhaustive search for $N = 20$.

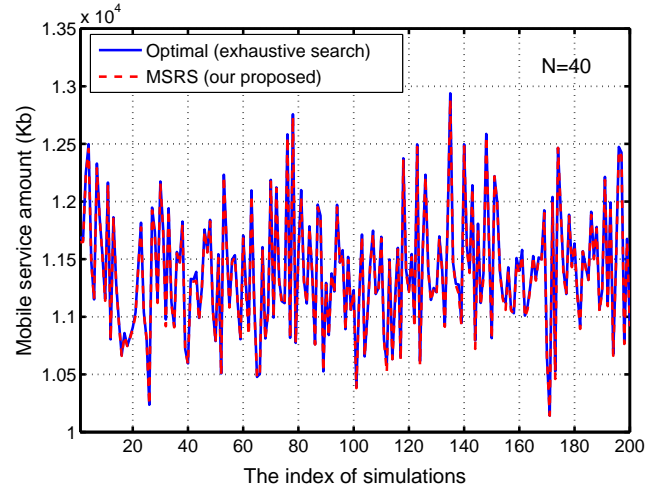


Fig. 5. Total mobile service amount comparison of MSRS and the exhaustive search for $N = 40$.

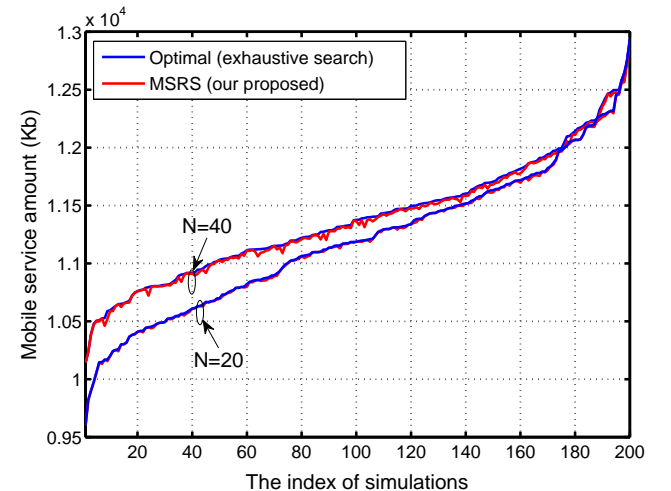


Fig. 6. Total mobile service amount comparison of MSRS and the exhaustive search in ascending order for $N = 20$ and $N = 40$.

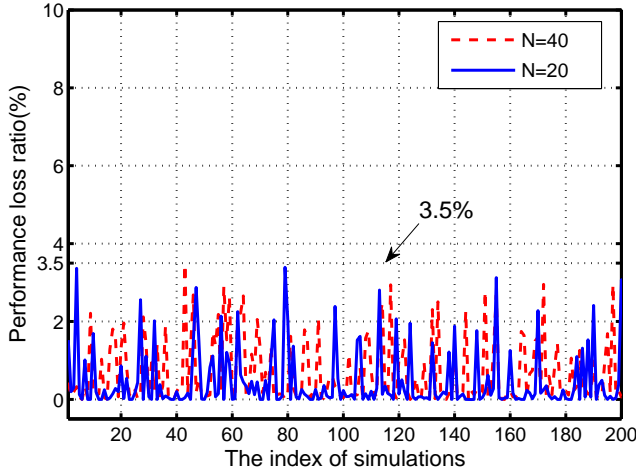


Fig. 7. Performance loss ratio of MSRS to the exhaustive search for $N = 20$ and $N = 40$.

C. Performance Comparison with IRRS and Tractional Non-cooperative Scheme

Then we compare the mobile service amount of our proposed MSRS with that of IRRS and the traditional non-cooperation scheme. The results is shown in Figure 8, where 200 simulation results are plotted for $N = 100$. Note that, the results in Figure 8 are also the sorted results in ascending order in terms of the mobile service amount of MSRS.

It also can be observed that, the total mobile service amount of MSRS is about 15 percents greater than that of the traditional non-cooperation scheme, which declares that by scheduling the VNs relatively close to the BS as helping RVs to perform cooperative relaying can greatly improve the system mobile service amount, since MSRS brings the cooperative communication benefit to vehicular networks. It also implies that by employing MSRS, the system average throughput and average spectral efficiency of vehicular networks can be greatly enhanced. Moreover, in Figure 8, it also can be observed that the total mobile service amount of MSRS are about 3.63 percent greater than that of IRRS. The reason is that MSRS is capable of characterizing the channel variations and topology changes of vehicular networks more accurately compared with IRRS.

D. Impacts of System Parameters on Performance

1) *The Impact of VN's Number on System Performance:* The mobile service amount of MSRS versus the number of VNs is plotted in Figure 9, where that of IRRS is also simulated as a benchmark. N is increased from 20, 40, ..., to 200. For each N , the plotted result is obtained by averaging 1000 independent implementations. It can be seen that, with the increment of the number of VNs, the mobile service amount of MSRS increases basically, but the increasing rate decreases with the increment of N . The reason is that more VNs may result in more AVs, which may decrease the RBS allocated to each VN and AV. Meanwhile, more VNs may provide more opportunities to find appropriate RV to help the

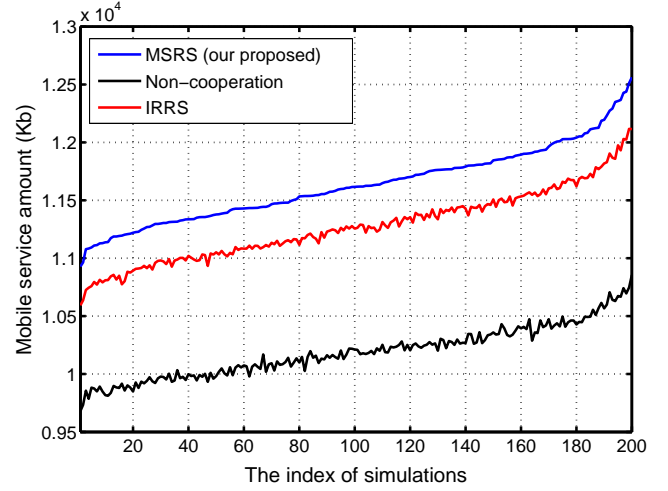


Fig. 8. The total mobile service amount comparison of MSRS, IRRS and traditional non-cooperation scheme

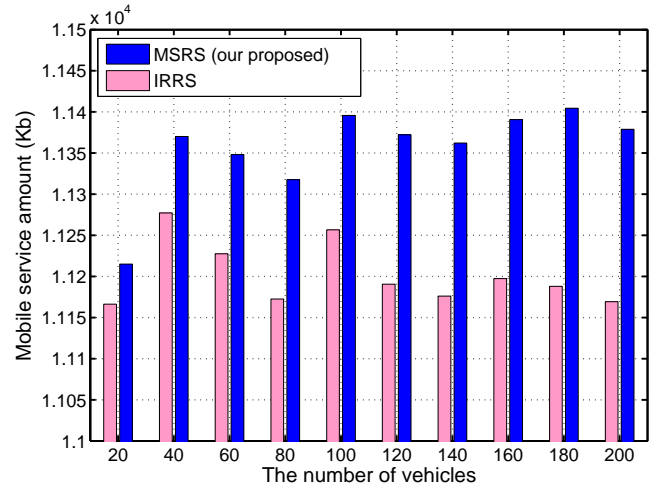


Fig. 9. The total mobile service amount of MSRS and IRRS versus the number of VNs.

AV. But for IRRS, its mobile service amount basically decreases with the increment of N .

2) *The Impact of Vehicles' Moving Speed on System Performance:* The mobile service amounts of both MSRS and IRRS versus vehicles' moving speed are presented in Figure 10 and Figure 11 for $N = 50$ and $N = 100$, respectively. The vehicle's moving speed is increased from 4m/s to 44m/s. The result shown in Figure 10 and Figure 11 for each value of speed was also obtained by averaging 1000 simulations.

In the two figures, one can see that the mobile service amount of both MSRS and IRRS decreases with the increment of vehicles' moving speed, but the mobile service amount of both MSRS decrease much slower than that of IRRS. Moreover, as shown in the two figures, when the vehicles are with a relatively high moving speed, e.g., 10m/s to 38m/s, the performance gain of MSRS to IRRS becomes large. When the vehicles are with a low moving speed and very high moving speed, the performance gain of MSRS to IRRS is small. The reason is that in low mobility case, the inaccuracy of using

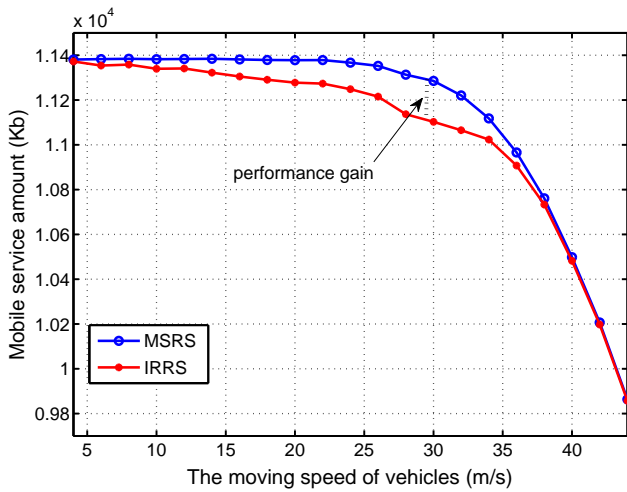


Fig. 10. The total mobile service amount of MSRS and IRRS versus vehicles' moving speed for $N = 50$.

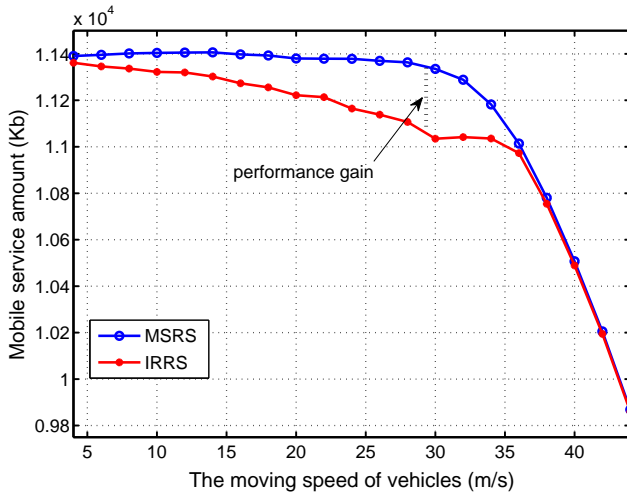


Fig. 11. The total mobile service amount of MSRS and IRRS versus vehicles' moving speed for $N = 100$.

the achievable instantaneous information rate to describe the system performance and to perform the scheduling is not large, and in very high mobility case, the moving spans of the vehicles within T are too large, which may increase the average distance between any pair of transmit and receiver, consequently decreasing the total mobile service amount of the whole system.

Nevertheless, it can be seen that MSRS always outperforms IRRS for various moving speeds. This demonstrates that MSRS has great potential in enhancing the information transmission capacity for mobile vehicular networks.

VI. CONCLUSION

In this paper, we introduced the mobile service amount to characterize the information transmission capacity of high-mobility V2V and V2I links. Based on this, we investigated the optimal relaying scheduling scheme to maximize the system total mobile service amount. In order to explore the system information transmission performance limit, we formulated an

optimization problem by jointly scheduling the V2I and V2V links. Since the problem is too complex to solve, we designed an efficient algorithm with low-complexity for it. Simulation results demonstrated that our proposed MSRS is able to work well like the optimal scheduling and our proposed MSRS is much more efficient for high-mobility vehicular systems.

REFERENCES

- [1] A.R. Beresford, J. Bacon, "Intelligent Transportation Systems," *IEEE Pervasive Computing*, vol. 5, no. 4, pp. 63-67, Dec. 2006.
- [2] J. P. Zhang, F. Y. Wang, K. F. Wang, W. H. Lin, X. Xu, C. Chen, "Data-Driven Intelligent Transportation Systems: A Survey," *IEEE Trans. Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1624-1639, Dec. 2011.
- [3] J. Petit, F. Schaub, M. Feiri, F. Kargl, "Pseudonym Schemes in Vehicular Networks: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 1, pp. 228 - 255, Jan. 2014.
- [4] L. Du, H. Dao, "Information Dissemination Delay in Vehicle-to-Vehicle Communication Networks in a Traffic Stream," *IEEE Trans. Intelligent Transportation Systems*, vol. 16, no. 1, pp. 66 - 80, Jan. 2015.
- [5] K. Shafiee, A. Attar, V. C. M. Leung, "Optimal Distributed Vertical Handoff Strategies in Vehicular Heterogeneous Networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 3, pp. 534 - 544, March 2011.
- [6] Q. Wang, P. Y. Fan, K. B. Letaief, "On the Joint V2I and V2V Scheduling for Cooperative VANETs With Network Coding," *IEEE Trans. Vehicular Technology*, vol. 61, no. 1, pp. 62-73, Jan. 2012.
- [7] M.F. Feteiha, H.S. Hassanein, "Enabling Cooperative Relaying VANET Clouds Over LTE-A Networks," *IEEE Trans. Vehicular Technology*, vol. 64, no. 4, pp. 1468 - 1479, April 2015.
- [8] K. Xiong, P. Y. Fan, Z. F. Xu, H. Yang, K. B. Letaief, "Optimal Cooperative Beamforming Design for MIMO Decode-and-Forward Relay Channels," *IEEE Trans. Signal Processing*, vol. 62, no. 6, pp. 1476-1489, March 2014.
- [9] H. Ilhan, I. Altunbas, M. Uysal, "Optimized Amplify-and-Forward Relaying for Vehicular Ad-Hoc Networks," in *Proc. IEEE VTC-Fall*, pp. 1-5, 2008.
- [10] M.F. Feteiha, H.S. Hassanein, "Cooperative vehicular ad-hoc transmission for LTE-A MIMO-downlink using Amplify-and-Forward relaying," in *Proc. IEEE GLOBECOM*, pp. 4232- 4237, Dec. 2013.
- [11] M. Seyfi, S. Muhaidat, J. Liang, M. Uysal, "Relay Selection in Dual-Hop Vehicular Networks," *IEEE Signal Processing Letters*, vol. 18, no. 2, pp. 134 - 137, Feb. 2010.
- [12] H. Zhou, P. Y. Fan, J. Li, "Global proportional fair scheduling for networks with multiple base stations," *IEEE Trans. Vehicular Technology*, vol. 60, no. 4, pp. 1867-1879, April 2011.
- [13] Q. Wang, D. O. Wu, P. Y. Fan, "Delay-constrained optimal link scheduling in wireless sensor networks," *IEEE Trans. Vehicular Technology*, vol. 59, no. 9, pp. 4564-4577, Sept. 2010.
- [14] Q. Zheng, K. Zheng, P. Chatzimisios, H. Long and F. Liu, "A novel link allocation method for vehicle-to-vehicle-based relaying networks," *Transactions on Emerging Telecommunications Technologies*, vol. 26, no. 5, early access, 20 Jan. 2014.
- [15] K. Zheng, F. Liu, Q. Zheng, W. Xiang, W. B. Wang, "A Graph-Based Cooperative Scheduling Scheme for Vehicular Networks," *IEEE Trans. on Vehicular Technology*, vol. 62, no. 4, pp. 1450 - 1458, May 2013.
- [16] C. Zhang, P. Y. Fan, Y. Q. Dong, K. Xiong, "Service-based high-speed railway base station arrangement," *Wireless Communications and Mobile Computing*, online published, 2013.
- [17] 3GPP TR 36.814, V9.0.0, "Further Advancements for E-UTRA, Physical Layer Aspects," Mar. 2010. [Online]. Available: <http://www.3gpp.org>
- [18] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments, IEEE Std. 802.11p-2010, 2010.
- [19] H. Khun, "The hungarian method for the assignment problems," *Naval Research Logistics Quarterly* 2, pp. 83-97, 1955.
- [20] L. Cheng, B. Henty, D. Stancil, F. Bai, and P. Mudalige, "A fully mobile, gps enabled, vehicle-to-vehicle measurement platform for characterization of the 5.9 GHz DSRC channel," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, pp. 2005-2008, 2007.

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